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OVERVIEW OF THE OREGON TRANSECT ECOSYSTEM RESEARCH PROJECT[1]

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Abstract. The Oregon Transect Ecosystem Research (OTTER) project is a study of ecosystem functions in coniferous forests using the methods of computer modeling, experimental and theoretical remote sensing, and ecological field and laboratory techniques. The study is focused on predicting the major fluxes of carbon, nitrogen, and water, and the factors that dynamically regulate them. The OTTER project was conceived to test two major questions: (1) Can a generalized ecosystem simulation model, designed to use mainly parameters available from remote sensing, predict the functioning of forests across an environmentally variable region? and (2) To what extent can the variables required by this model be derived from remotely sensed data? The scientific objectives and scope of the project demanded that a coordinated effort be made to link ground measurements with remote sensing and modeling requirements. OTTER was selected as a focus for a National Aeronautics and Space Administration (NASA)-sponsored Multi-sensor Aircraft Campaign (MAC; combining NASA aircraft and sensors with those of others) on the basis of experience gained in past ecosystem studies and remote-sensing projects, and the importance of the OTTER objectives to NASA's long-range science goals and plans. Having several independent approaches available, both on the ground and from various remote-sensing platforms, proved valuable in estimating and validating many of the critical variables. This experience and cross comparison should help simplify future studies of a similar nature. Edited data sets from the OTTER project are now available to the scientific community on optical disks or via on-line data banks at NASA (Washington, D.C., USA) and Oregon State University (Corvallis, Oregon, USA).

Key words: coniferous forests; cooperative research; data base; ecological fluxes; ecosystem simulation; Oregon transect; OTTER project; remote sensing.

INTRODUCTION AND BACKGROUND

In the last decade much of our understanding of how ecosystems function has been formalized into mathematical models. Ecosystem simulation models now exist to estimate the rates of many important functions, but to run these models over extensive regions requires measurements not easily obtainable. For example, nearly all ecosystem models require knowledge of the incoming solar radiation and of the ability of vegetation to absorb this radiant energy. While these two variables are fairly simple to monitor on the ground, few examples exist where they have been monitored together over more than one growing season—and fewer yet have been monitored over large geographic regions using remote sensing. Most ecosystem models also require detailed knowledge of soil nutrient conditions or availabilities and of soil water storage capacity. These two variables, however, are extremely difficult to measure accurately, and only recently has a potential means been found to estimate the former by remote-sensing methods (Aber et al. 1989*a*). When changes occur, dynamically with climate or phenology, or through some type of disturbance, repeated measurements become necessary and are very difficult to obtain over extensive areas.

Much of what we know about the structure and function of the forests of the Pacific Northwest region of the United States is from studies initiated two decades ago as part of the International Biological Programme (IBP) (Waring and Franklin 1979, Reichle 1981, Edmonds 1982). This program collected intensive climatic and ecological data from what is now the National Science Foundation (NSF)-sponsored Long-Term Ecological Research site at the H. J. Andrews Experimental Forest in Oregon. Similar sets of data were obtained from younger forests in Washington state. From data collected in these two areas, and research in Colorado, mechanistic ecosystem models were formulated to match observations made on rates of growth, litterfall production, litter decomposition, evapotrans-

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piration, photosynthesis, and streamflow (Running et al. 1975, Waring and Running 1976, Sollins et al. 1981). The problem when applying these models over large regions, especially if the parameters are derived from remote-sensing data, is how to make reliable predictions without losing the site-specific, fine-scale information required.

Remote-sensing data are generally unable to directly measure ecosystem fluxes but can be used to estimate some of the key state and condition variables related to these fluxes and simulated in ecosystem models. Satellite and airborne remote-sensing data have been used successfully to map changes in land cover and condition. Ecosystem characteristics such as leaf area index, absorbed photosynthetically active radiation, standing biomass, canopy water status, and the biochemical composition (nitrogen and lignin) of forest canopies have been estimated from remote-sensing data, but with less certainty. These variables can be used in ecosystem simulation models, such as the model of Running and Coughlan (1988), which has been applied in a general way across large regions (Running et al. 1989). However, no tests or test data sets have been available to study these methods for the full combination of carbon, nitrogen, and water interactions. Accordingly, a primary goal of the Oregon Transect Ecosystem Research (OTTER) project was to evaluate the full spectrum of remote-sensing data and algorithms that can meet the parameter requirements of ecosystem models to assess ecosystem structure and function. If these methods can be validated, they can then be applied to the large regional extent available from remote sensing.

The OTTER project was designed to develop a basis for eventually extrapolating point measurements and estimates of ecosystem structure and function across larger geographic regions. Before this becomes possible, two major questions must be answered: (1) Can a generalized ecosystem simulation model (FOREST-BGC; Running and Coughlan 1988, Running and Gower 1991) predict variations in functioning of forests across an environmentally variable region? and (2) To what extent and with what limitations can the variables required by this model be derived from remote-sensing data? The large environmental gradients of western Oregon provide the experimental variation for investigating both of these questions. Any geographic transect across west–central Oregon covers a broad range of climate regimes and associated forest types, a range that represents most climate types found in the north-temperate zone. The OTTER project included ground-based measurements of many variables needed to initialize the model, to drive the model, and to validate the predictions of the model and of remote-sensing analyses. This paper describes the overall project, the design of experiments, and the effort made throughout the project to coordinate modeling, remote sensing, and ground-based measurements.

Remote Sensing Research Linked to Ecosystem Research

Running and Coughlan (1988) developed a general mechanistic ecosystem model for forests that simulates the fluxes of carbon and water, and later expanded it to include nitrogen (Running and Gower 1991) and the interactions and controls of all three within and through the system. This ecosystem model, called FOREST-BGC (BioGeochemical Cycling) served as the keystone of the OTTER project. The model was originally conceived to operate on parameters that could ultimately be derived from remote sensing. FOREST-BGC represents a series of interlinked hypotheses that specify the way that water, carbon, and nitrogen move through a forest ecosystem and the mechanisms that regulate these fluxes. On the basis of previous research, we could identify the variables required to initialize, to run, and to confirm the simulations.

For a number of years preceding OTTER, remote-sensing research had been carried out to develop methods to derive many of the variables required by FOREST-BGC. A variety of remote-sensing data has been examined and the continued development of new sensors has opened the opportunity to enhance these methods or to provide additional variables. The basic questions that must be addressed in linking ecosystem modeling to remote sensing are: (1) What variables must be derived? (2) What variables can be obtained from remote sensing? and (3) What limitations must be recognized and addressed in using remotely sensed data?

Standing biomass (and maintenance respiration)

In earlier versions of FOREST-BGC the calculation of maintenance respiration was scaled as a function of leaf area index. However, standing biomass is physiologically related to this variable but has been a difficult variable to derive from remote sensing on a point-by-point basis. Regional estimates of total forest biomass and volume were estimated for forested regions of Oregon as early as 1976 using data from the Landsat MSS system (Douglas County; Peterson and Card 1977). These estimates were based on multistage sampling using a Landsat classification as the first-stage estimator and aerial photography and ground plots as the second and third stage estimators, respectively. While these estimates are accurate for a region, they do not predict well for single points or sites. Approaches that are suitable for a continuous mapping of standing biomass use either the optical properties or the backscattering properties to a radar source. In the former, Li and Strahler (1986) explain the brightness variation in remote-sensing data by treating the trees as geometrical objects, such as cones, with illuminated and shadowed parts, over shaded or illuminated backgrounds. The spacing and sizes of the trees can be used to calibrate the image brightness and then the model can be inverted to calculate biomass (see Wu and Strahler 1994 [this issue]). Standing wet biomass with fixed forms, such as boles of trees, interacts with a radar beam to alter the backscattered signal (Durden et al. 1989, Kasischke and Christensen 1990). The backscatter signal can be modeled and then inverted to estimate the components responsible. Each of these methods have proven useful in low-density forests. The challenge to each of these approaches is whether they are able to quantitatively discern variations in standing biomass of dense forests above 100–200 Mg/ha in a region such as Oregon where maximum standing biomass of forest can exceed 1000 Mg/ha.

Leaf area index (and ecosystem–atmosphere exchange)

The surface area of foliage available to intercept light, transpire water, and exchange carbon dioxide is another structural index of key importance in ecosystem function. FOREST-BGC uses leaf area index (LAI) in many ways to calculate ecosystem exchange rates. The well-known optical properties of leaves—strong chlorophyll absorption in the visible spectrum and strong scattering or diffuse reflectance in the near infrared—provide a basis for estimating LAI using remote sensing. Many studies have shown canopy reflectance of solar radiation as measured by remote sensors can be related to variations in LAI. For example, red reflectance is inversely and asymptotically related to LAI while near infrared (NIR) reflectance is directly proportional to LAI. The ratio of these two observations, NIR/red (the so-called "Simple Ratio"), using data from the Landsat Thematic Mapper (TM) has been shown to be directly and slowly asymptotically related to seasonal maxima of LAI in the conifer forests of Oregon (Peterson et al. 1987, Spanner et al. 1990*a*). Comparable results have been found for the coarser (1 km vs. 30 m) data of the Advanced Very High Resolution Radiometer (AVHRR), a National Oceanographic and Atmospheric Administration (NOAA) satellite with daily coverage of the world for western coniferous forests (Spanner et al. 1990*b*). Use of only the seasonal maxima in FOREST-BGC simulations would overestimate fluxes. In OTTER we chose to estimate the seasonal variation in LAI using both TM and AVHRR data. This introduces additional problems having to do with large variations in illumination and atmospheric conditions, directional views of AVHRR, all convolved with the seasonal variability of LAI (see Spanner et al. 1994, Pierce et al. 1994).

Intercepted photosynthetically active radiation (IPAR) (and photosynthesis)

The actual amount of IPAR sets the maximum available energy for conversion of carbon dioxide to photosynthate. LAI is related to this maximum amount in an exponential way. Thus, the relationship of IPAR to the Simple Ratio is approximately exponential as well. A transform of the Simple Ratio, called the "Normalized Difference Vegetation Index" (NDVI), tends to linearize this relationship (Sellers 1987). While global maps of NDVI have been generated from the AVHRR data (Tucker et al. 1985) and used in models of carbon dioxide exchange (Fung et al. 1987), they are difficult to validate. And, in regions of considerable disturbance, the NDVI values are complicated by the high spatial variation in cover conditions. In OTTER we have attempted to estimate the dynamic variations in IPAR using a variety of field spectral instruments and remote-sensing data, from very fine (1–2 m) to coarser (30–1000 m) spatial scales (Goward et al. 1994*b*).

Solar radiation (and photosynthesis)

Cloud cover affects the fraction of solar radiation that reaches ecosystems as well as the ratio of direct to diffuse radiation. Studies of cloud cover over fairly flat terrain, such as the plains of the central United States, have shown that cloud cover as a mean monthly estimate can be obtained from data obtained from the GOES satellite (Eck and Dye 1991). The Total Ozone Mapping Spectrometer (TOMS) is sensitive to ultraviolet light reflected from clouds and integrates this measure over its 2.5 × 2.5° field of view at nearly hourly intervals. The accuracy and suitability of these measurements over mountainous terrain remains largely unexplored (Goward et al. 1994*b*).

Ambient air temperature (and ecosystem fluxes)

In addition to the estimates of foliar amount intercepting PAR, one needs to know the temperature constraints on photosynthesis, respiration, transpiration, and other processes. When the air is less than saturated with water vapor, a deficit or atmospheric demand is created that can influence stomatal behavior in many plants of western Oregon even with adequate supplies of soil water (Running et al. 1975, Marshall and Waring 1984, Runyon et al. 1994 [this issue]). Remotely sensed canopy temperatures can be used to estimate nighttime minimum air temperatures. A freezing temperature can lead to closed stomates the following day. And previous work has shown that the minimum nighttime temperature approaches dewpoint temperature, allowing a calculation of the absolute humidity (Running et al. 1987). The AVHRR satellite acquires both daytime and nighttime temperature fields. The daytime data can be used to scale the absolute humidity for relative humidities during the day. Thermal infrared sensors have the capacity to estimate the integrated or brightness temperature of ecosystems under clear sky conditions (Luvall and Holbo 1989). In an open forest or a disturbed one, the sensor integrates objects at a variety of temperatures, giving a composite brightness temperature. However, the aerodynamically rough and tall coniferous forest under closed-canopy conditions is closely coupled to the surrounding ambient air temperature, making these areas ideal for sensing ambient air temperature. In OTTER we chose to make direct measurements of ambient air temperature at meteorological stations near each site studied with which to validate the remotely sensed temperatures.

Soil moisture, temperature, and drought (and stomatal behavior)

Soil moisture varies a great deal in forests of Oregon due to summer drought and often low soil water holding capacities. As soils dry out, this exerts an increase in resistance to water flow into tree roots, which is reflected in an increase in stomatal resistance. Again, sensor brightness temperatures may help to discern these situations. The integrated temperatures described above include heated soils as well as the canopy temperatures—the temperature field determined in part by the moisture status of the various cover types being sensed. Nemani and Running (1989) hypothesized that areas of low LAI or low values of NDVI should have elevated temperatures relative to the temperatures of the nearby forest canopy, and that the slope of the relationship between NDVI and brightness temperature over a small region could be an index to drought stress and stomatal resistance. At the same time, areas of high NDVI would measure ambient air temperatures. These hypotheses were further evaluated in OTTER using sensors from low-flying aircraft and from satellites (Waring et al. 1993, Goward et al. 1994*b*).

Canopy biochemical contents (and nutrient cycling and photosynthesis)

The biochemical composition of foliage is a potential index to the rates of nutrient cycling and to the maximum rates of photosynthesis (e.g., Field and Mooney 1986, Aber et al. 1989*b*). The chlorophyll content is related to photosynthetic capacity (Yoder 1992), while nitrogen concentration has been related to the rate of nitrogen turnover and to productivity (Vitousek 1984). Meentemeyer and Berg (1986) and Melillo et al. (1982) have shown that the lignin-to-nitrogen ratios are a determinant of the rates of decomposition, while lignin concentrations have been inversely related to the annual rate of nitrogen mineralization in deciduous forests (Aber et al. 1989*b*). Myrold et al. (1989) studied the annual rates of N-mineralization across a transect of Oregon and correlated N-mineralization, microbial biomass, and soil respiration to LAI and climate. The balance of these relationships can be changed by chronic additions of nitrogen via acid deposition, wherein the excess nitrogen availabilities can lead to changes in the lignin-to-nitrogen ratios and concentrations (Aber et al. 1989*a*). Much less is known about the seasonal variations in nutrient-cycling processes and the effects of fertilization. In OTTER, studies were conducted on these effects through use of control and fertilization experiments (see Matson et al. 1994 [this issue]).

The remote sensing of plant biochemical composition has been based on the recent access to very high spectral resolution instruments and on the understanding of how organic bonds produce differential absorption in the visible and shortwave infrared regions. Well known are the absorptions due to chlorophyll and the accessory pigments and the effect they create on the position of the red edge, the long wavelength end of the absorption spectrum near the infrared. Estimates of chlorophyll contents by detection of the position of the red edge were conducted in OTTER using several instruments and various radiative transfer models (Johnson and Peterson 1991, Johnson et al. 1994). The harmonics, overtones, and combination bands produced by fundamental vibrations of the organic bonds of the other biochemicals tend to occur in the shortwave infrared region. While evidence suggests that some of these properties may be predicted from high spectral resolution imaging spectrometer data (e.g., lignin concentrations by Wessman et al. [1988]; nitrogen by Peterson and Running [1989]), the general application of these methods is still in question. For example, there are concerns about the covariance with water content, itself dominating the shortwave infrared spectrum. Other structural variations as well as species compositional changes also cloud the interpretation. Oregon—with its extensive coniferous forests of a few species and with the fertilization experiments—offers conditions for testing whether the biochemical composition of forest canopies can be sensed remotely (see Johnson et al. 1994, Matson et al. 1994 [this issue]).

Design of the Experiment

Six study sites were selected from forest ecosystems across the temperature–moisture gradients of Oregon. These six sites are located along a roughly west-to-east transect between 44° and 45° north latitude beginning at the coast and extending inland ≈250 km. The location of the sites is shown in reference to an AVHRR (Advanced Very High Resolution Radiometer) false color image of western Oregon (see *Intercepted photosynthetically active radiation . . .*, above) (Fig. 1). The transect begins near Cascade Head Experimental Forest, north of Lincoln City along the Pacific coast. It extends 250 km to the east to a juniper woodland near Redmond in the high desert interior of Oregon. The names and numerical codes associated with each site are provided in Table 1 with detailed descriptions provided in Runyon et al. (1994 [this issue]). Climate variation across the transect is extreme, with precipitation ranging from ≈250 cm to 25 cm/yr, west to east. The coastal and valley sites (1O, 1G, and 2) rarely experience snow. The subalpine forest (site 4) experiences moderate to deep snowpack every year, and freezing temperatures persist for much of the winter, both here and at sites 5 and 6. Drought is extreme in the Willamette Valley (site 2), the Ponderosa pine site (5), and

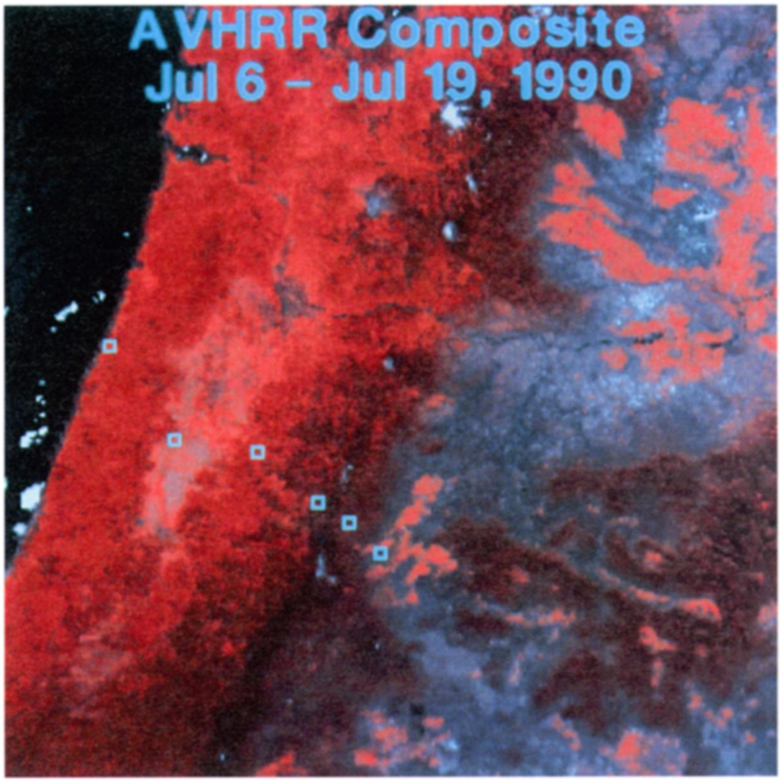

FIG. 1. AVHRR false-color composite image of northwestern Oregon overlaid with the approximate locations of the six study sites. Red tones indicate vegetation of all types. Darker reds are usually conifer forests, brighter reds are agricultural lands and broadleaf forests; bluish tones are dry desert areas with bare soils; and the small white areas are a few clouds or snow. This image is a composite of individual daily AVHRR images; clouds are minimized and only the highest brightness values related to vegetation are retained point by point throughout the image.

the juniper woodland (site 6). Leaf area indices and net primary productivity vary by more than 10-fold across the transect.

Understanding the role of nitrogen in controlling the rates of various ecosystem processes led to additional sites and measurements across the transect. At the coastal Cascade Head site (1), we selected a stand of deciduous nitrogen-fixing alder (*Alnus rubra*, site 1A); at site 3, Scio, a *Tsuga heterophylla–Pseudotsuga menziesii* stand was selected that had been fertilized (site 3F) and part of that stand continued to be fertilized twice a year throughout the duration of the 3-yr OTTER project (site 3IF). Finally, a stand of Ponderosa pine (*Pinus ponderosa*) receiving surface application of sewage sludge for the 5 yr previous to this project was selected near site 5 (Metolius: site 5F). Each of these four sites were compared to the control or untreated sites.

Seasonal coverage

Four principal campaigns were planned to match changes in ecosystem function throughout the year. The timing of these campaigns was based on the following seasonal criteria:

TABLE 1. Names and numerical codes for the six primary and five ancillary study sites of the OTTER project in Oregon.

Numerical code	Name	Geographical location		Primary species/treatments
		Lat. (°N)	Long. (°W)	
1G	Cascade Head (Gholz' site)	45°03′	123°57′30″	*Tsuga heterophylla*/control
1A	Cascade Head (alder)			*Alnus rubra*/nitrogen fixation
1O	Cascade Head (old growth)			*Tsuga heterophylla*/old growth
2	Waring's Woods (the Corvallis site)	44°36′	123°16′	*Pseudotsuga menziesii*
3C	Scio	44°40′30″	122°36′40″	*Pseudotsuga menziesii*/control
3F	Scio (fertilized)			*Pseudotsuga menziesii*/single fertilization
3IF	Scio (intensively fertilized)			*Pseudotsuga menziesii*/double fertilization
4	Santiam Pass	44°25′20″	121°50′20″	*Tsuga mertensiana*
5C	Metolius	44°25′	121°40′	*Pinus ponderosa*/control
5F	Metolius			*Pinus ponderosa*/fertilized
6	Juniper	44°17′30″	121°20′	*Juniperus occidentalis*

TABLE 2. Ecosystem and environmental variables and processes measured, remotely sensed, and simulated by ecosystem and radiative transfer (RT) models.

Variable: Processes	How measured	Remotely sensed*	Simulated (models)† Ecosystem	Simulated (models)† RT	Principal scientists
Meteorological:					
Incident shortwave solar radiation	Meteorological station				R. McCreight and J. Runyon
Cloudiness		TOMS			S. Goward and D. Dye
Precipitation	Meteorological station				R. McCreight and J. Runyon
Air temperature	Meteorological station		MT-CLIM		R. McCreight and J. Runyon; J. Glassy
Humidity	Meteorological station		MT-CLIM		R. McCreight and J. Runyon; J. Glassy
Soil temperature	Direct at site				D. Myrold and R. Waring
Optical depth (atmospheric)		Sunphotometer Reference panels		Wrigley et al. 1992	M. Spanner R. McCreight
Ecophysiological and nutrient cycling:					
Pre-dawn water potentials	Pressure bomb		FOREST-BGC		R. Waring; S. Running
Photosynthesis	Gas exchange		FOREST-BGC		B. Yoder; S. Running
Conductance	Gas exchange	AVHRR; Ultralight	FOREST-BGC	Nemani and Running	B. Yoder; R. Waring and S. Goward; S. Running
Litterfall	Field meas.		FOREST-BGC		D. Myrold and B. Claycomb; S. Running
N-mineralization	Field tech.		FOREST-BGC		D. Myrold and P. Claycomb; S. Running
Soil water storage	Field methods				D. Myrold and P. Claycomb; J. Runyon
Soil properties	Field methods				D. Myrold and P. Claycomb
Soil respiration	Field chambers		FOREST-BGC		K. Mattson; S. Running
Maintenance respir.	Field methods				M. Ryan
Stand growth	Stem cores		FOREST-BGC		R. Waring and J. Runyon; S. Running
Growth respiration			FOREST-BGC		S. Running
Decomposition rate	Field methods		FOREST-BGC		D. Myrold and P. Claycomb; S. Running
Evapotranspiration			FOREST-BGC		S. Running and J. Glassy
Canopy and tree biophysical characteristics:					
Spectral reflectance of components	Field and laboratory spectrometers	Truckboom and ultralight spectrometers			S. Goward and F. Huemmrich; L. Johnson; A. Strahler; S. Ustin; R. McCreight; B. Law; J. Miller
Intercepted photosynthetically active radiation	Ceptometers	AVHRR; Ultralight TMS, NS001; AVIRIS CASI; FLI			R. McCreight and R. Waring; S. Goward; M. Spanner; L. Johnson; J. Miller, P. Gong and J. Freemantle
Leaf area index (LAI)	Ceptometers LI-COR LAI meter	AVHRR; TMS; AVIRIS; CASI; FLI; NS001	FOREST-BGC	Miller et al.	M. Spanner; L. Johnson; S. Running; J. Welles; J. Miller and P. Gong
Biomass, standing	Field cruise	ASAS; TMS		Geometric optics	A. Strahler and W. Yucheng
		AIRSAR		Microwave model	S. Durden and M. Moghaddam
Hemispherical albedo		ASAS; Ultralight		Geometric optics	L. Johnson; A. Strahler; R. McCreight
Canopy temperature	AirTherm*	TIMS			R. McCreight

TABLE 2. Continued.

Variable: Processes	How measured	Remotely sensed*	Simulated (models)† Ecosystem	RT	Principal scientists
Leaf and canopy biochemical characteristics:					
Chlorophyll	Wet chemistry	CASI; FLI; AVIRIS		Miller; PROSPECT	C. Billow and P. Matson; J. Miller; L. Johnson
Nitrogen, lignin	Wet chemistry	AVIRIS			C. Billow and P. Matson; L. Johnson
Cellulose, starch	Wet chemistry	AVIRIS			C. Billow and P. Matson; L. Johnson
Amino acids	Wet chemistry				C. Billow and P. Matson

* Sensors: AIRSAR = Airborne Synthetic Aperture Radar; AirTherm = Teletemp model 43 infrared radiometer; ASAS = Advanced Solid-state Array Spectrometer; AVHRR = Advanced Very High Resolution Radiometer; AVIRIS = Airborne Visible-Infrared Imaging Spectrometer; CASI = Compact Airborne Spectrographic Imager; FLI = Fluorescence Line Imager; TIMS = Thermal Imaging Multi-channel Scanner; TMS = Thematic Mapper Simulator (also: NS001); TOMS = Total Ozone Mapping System.

† Models: MT-CLIM = mountain climatology model, Running et al. (1987); FOREST-BGC = mechanistic ecosystem simulation model, see Running and Coughlan (1988), Running and Gower (1991); Geometric optics = radiative transfer code of Li and Strahler (1986); Nemani and Running (1988) = method developed to estimate stomatal resistance based on brightness temperature and vegetation index; Miller et al. (1990) = model fitting spectral curves at the red edge to predict chlorophyll and LAI; PROSPECT = model to simulate the visible-infrared spectrum of leaves; Jacquemond, S. and F. Baret (1990); Microwave = unnamed model used by Durden et al. (1989) to simulate backscatter return of vegetated scenes.

(1) February–March: pre-budbreak conditions at all sites, when leaf area is at a minimum and low temperatures are likely to be constraining many ecosystem processes;

(2) May–June: budburst period when soils are near saturation, and maximum rates of many ecosystem processes should be observed;

(3) August: full expansion of foliage on all sites and the probability of drought is high; and,

(4) September-October: foliage of deciduous trees and shrubs is in full autumn color and rainfall has normally begun to recharge soils; freezing temperatures are unlikely to extend through the day.

Ecological and meteorological measurements

Table 2 indicates the kinds of data collected in the field for ecological analysis. Meteorological data including air temperature, relative humidity, precipitation, and shortwave (400–1200 nm) incoming radiation were recorded by minute and stored as hourly averages (see Runyon et al. 1994 [this issue]). While we chose to locate a meteorological station in clearings near each site (except site 6), the distance from the actual site to the station location still necessitated some minor corrections using the model MT-CLIM (Running et al. 1987).

In contrast to the meteorological measurements, much of the physiological data were gathered at seasonal intervals or in conjunction with the campaigns. The highest priority was placed on measurements of pre-dawn water potentials. These values best characterize the intensity of drought on vegetation and set the upper limits on potential gas exchange.

Structural data on each stand were collected with techniques modified from those that foresters apply to assess timber volumes. Allometric relations equate tree diameter or sapwood cross-sectional area to the biomass of foliage, branches, and stems. Additional data on tree heights and the length and widths of tree crowns were also measured (see Wu and Strahler 1994 [this issue]). Growth was estimated by measuring ring widths on cores extracted from sampled trees at each site. The foliar biomass of understory plants in most sites was not a large fraction of total foliar biomass except the easternmost sites. At site 5, a Ponderosa pine site where most of the overstory had been removed through harvesting, a significant understory component is present. This understory biomass and LAI (leaf area index) was carefully measured and analyzed (see Law and Waring 1994). A variety of indirect methods was used to estimate LAI and checked against the allometric approach. In general, our estimates of annual aboveground net primary production and of foliar biomass were based on the overstory trees only.

Leaf litterfall, an important variable for checking model predictions of carbon and nitrogen cycling, was measured only at sites 1 and 3. We used previously collected data from the IBP (Forest Science Data Bank) and published information on leaf turnover to provide estimates of leaf litterfall at the other sites. D. Myrold and his colleagues in the Soil Science Department of Oregon State University measured nitrogen cycling parameters such as nitrogen mineralization (net and total), ammonification, nitrification, microbial biomass, soil CO_2 respiration (measured by K. Mattson of the University of Idaho), and various soil properties through the year in situ. Soil and litter moisture conditions were measured at the time of the campaigns. Summary values of these variables have been added to the data base (see *Data storage and retrieval,* below).

During each of the four campaigns, foliage was collected by Oregon State University personnel and

TABLE 3. Airborne and satellite platforms and sensor systems, including ground-based instruments, used in the OTTER project.

Altitude	Platform	Sensor*	Time of day
Satellite	NOAA 9,10 GOES	AVHRR TOMS	1400
20 000 m	ER-2 aircraft	AVIRIS TMS TIMS CIR (color infrared aerial photography)	Noon
10 600 m	DC-8 aircraft	SAR	Noon
4500 m	C-130 aircraft	ASAS NS001 TIMS CIR Sunphotometer (sun-tracking)	Noon, morn/afternoon
600 m	Apache light plane	FLI	Noon
450 m	Cessna light plane	Spectron (modified)	Noon
150–450 m	Ultralight aircraft	Spectron, AirTherm	Noon, morn/afternoon
6 m	Truckboom	Spectron SE590 Barnes MMR	
Ground	Portables	Spectron SE590 and SE 393, ALEXA, SIRIS, LI-COR, Barnes MMR, Ceptometers, fisheye lens, digital camera, Sunphotometer	

* CIR = color infrared aerial photography; SAR = synthetic aperture radar; MMR = MultiModular Radiometer. Other sensor acronyms are explained in Table 2.

shipped on dry ice to NASA Ames Research Center for wet chemical analysis (see Matson et al. 1994 [this issue]). These samples were analyzed for a number of biochemical constituents including chlorophyll *a* and *b*, amino acids, nitrogen and protein contents, lignin and cellulose, and the labile carbohydrate, starch. Some of these samples were also measured spectrally in laboratory spectrophotometers for later correlation analysis with the biochemical composition.

The ecosystem model, FOREST-BGC, requires accurate estimates of water storage capacity in the root zone. Previous information gathered by Gholz (1982) was used in the modeling analysis, but these data have proved to be in error due to inaccurate estimates of rooting depth and due to spatial variability in soil properties (see Running 1994 [this issue]). No further attempt to independently estimate soil water holding capacity has been made.

Remote-sensing measurements

Past remote-sensing research coupled to the development of FOREST-BGC had identified many of the variables we felt were possible to retrieve from remote-sensing data. However, much of this work had concentrated on forests at peak mid-season condition or on forests distributed throughout the north-temperate zone. In addition, the development of new sensors operating from aircraft had opened up new approaches to the retrieval of these variables, potentially resolving limitations observed in earlier studies, or potential access to new variables, such as hemispherical albedo and standing biomass, that were unavailable earlier. Moreover, there is the potential for synergy by combining sensors of a wide variety including radar sensors when all of the sensors acquire data at the same time and under similar conditions. This allowed us to examine questions about the robustness of algorithms to remove atmospheric effects, for example, or to compare the consistency and information content of different sensors operating with a range of spatial and spectral scales. We sought to determine under what conditions and with what techniques each remote-sensing instrument could provide valid estimates of the various biophysical and biochemical parameters across the transect and at each site. And—for the first time for these forests—we sought to examine these parameters for seasonal variation.

Table 3 presents the spectral measurements in three components: ground point observations, airborne and satellite imaging and point observations, and observations of the atmosphere. Table 2 provides a summary of these measurements, the sensor and radiative transfer model used (if any), and the investigator involved. J. W. Skiles and G. L. Angelici (contractor report 4557 [1993] to National Aeronautics and Space Administration) provide a complete description of each sensor and the record of data acquired and available through the data bank.

Ground: Spectral measurements of forest components.—The interpretation of the composite reflectance signals of imaging sensors requires knowledge of the spectral reflectance of the components of the object, the forest, including foliage, branch, and stem bark, litter, and soil. At most sites these data were acquired both under natural solar illumination in the field using spectroradiometers and under controlled illumination using laboratory spectrophotometers (Goward et al. 1993). Some of the samples collected for biochemical assays were also measured as whole leaves in laboratory spectrophotometers.

A number of investigators brought similar spectroradiometers to the field for these measurements. Although many of these instruments were purchased from the same manufacturer or had similar spectral band widths and sensitivities, the intercalibration of these instruments was compared in the field for wavelength accuracy. Variations as great as 20 nm were observed between instruments of the same manufacture.

Variation in radiometric sensitivity was frequently checked against white reference panels under a range of different illumination conditions, derived from solar or artificial illumination sources. Spectrally "flat fields" consisting of asphalt parking lots, bare soil, or gravel pits were located near each site to serve as references for both field spectrometers and for the sensor data. These flat fields were used to monitor spectral performance between sensors and throughout the seasons of the campaigns. Radar sensing requires a different source for calibration, consisting of large triangular sheets of aluminum assembled into a corner reflector. Three such reflectors were positioned near sites across the transect.

Satellite and airborne sensors.—Virtually every remote-sensing instrument currently available and used for biospheric studies was included in OTTER, and their properties are shown in Table 3. Each sensor has a unique instantaneous field of view or ground resolution, different spectral bandwidths and view angles, and differences in radiometric performance. Although one can use some sensors to derive more than one of the required variables, each sensor often has optimum characteristics for specific parameters. A brief review of the sensors used in OTTER follows.

1. *Advanced Very High Resolution Radiometer (AVHRR).*—The frequent (four times daily) coverage of the Earth by AVHRR, operating from a NOAA satellite in polar orbit, the spectral band placement, and the broad geographic swath widths of the 1-km spatial resolution data make AVHRR data particularly useful for monitoring processes that vary slowly across the landscape at this scale, such as IPAR (intercepted photosynthetically active radiation) and canopy temperature, but which vary more rapidly from day to day. AVHRR data were acquired for clear or cloud-free conditions across the transect from the EROS Data Center of the U.S. Geological Survey in Sioux Falls, South Dakota. The near-infrared and red bands of AVHRR were transformed into the NDVI and used to calculate seasonal changes in IPAR and LAI. The thermal channel was used in conjunction with the NDVI values to estimate stomatal resistance. The broad swath width of AVHRR (several thousand kilometres) introduces large and significant variations in ground viewing angles, solar illumination conditions, and atmospheric path length. These directional effects must be understood to make the best use of these data.

2. *Landsat Thematic Mapper (TM) and airborne Thematic Mapper Simulator (TMS).*—Unlike the AVHRR, the Landsat TM observes any point on Earth only every 16 d, even though it, too, is in polar orbit. This is because of the narrow swath width ($\approx$100 km) and higher spatial resolution. Such infrequent coverage is, however, a disadvantage in cloudy regions such as the Pacific Northwest. Since we had to coordinate the data collection efforts of many sensors in short time-window campaigns, we chose to use the airborne simulator, TMS, operating at 20 km from NASA's ER-2 high altitude aircraft. The TM and the TMS have narrower, though similar, bandwidths than AVHRR, supplemented by channels in the blue, green, and short-wave and thermal infrared. Moreover, TM and TMS have a spatial resolution of 30 m, useful for resolving smaller targets such as forest stands or for mapping high-frequency changes in cover conditions at scales common to most ecological work.

For the OTTER project, TMS data were used to calculate seasonal and across-transect variations in LAI, standing biomass, and IPAR. A similar sensor, called the NS001 Thematic Mapper simulator, operating from NASA's C-130 aircraft at 5–8 km was also used to collect data and had the additional advantage of having on board a sun-tracking sunphotometer. This sensor observes the solar disk at the position of the sensor and its data are used to calculate additive atmospheric effects on the NS001 data from the ground up to the aircraft altitude.

3. *Thermal Infrared Multi-channel Scanner (TIMS).*—This instrument includes four thermal infrared channels between 8 and 12 μm that measure emitted thermal radiation from the Earth's surface. Though designed initially for geologic studies, TIMS data have been used in studies of ecosystem temperatures and used in energy balance models of evapotranspiration. The TIMS operates from the C-130 aircraft and its data were collected simultaneously with the NS001 data. The TIMS data have not been used in any OTTER analysis as yet, but for completeness, are available to future scientists for analyses (see *Data storage and retrieval,* below).

4. *Airborne Synthetic-Aperture Radar (AIRSAR).*—AIRSAR is a side-looking imaging radar system making measurements of backscattered and polarized radiation emitted by the sensor system in three frequen-

cies called L, C, and P bands. AIRSAR produces images with a spatial resolution of ≈30 m while operating from the NASA DC-8 aircraft at ≈15 km. We obtained data with AIRSAR in March, June, and August to assess whether variations in standing biomass across the transect could be detected quantitatively (Moghaddam et al. 1993) and to test whether the drought conditions of August relative to the wet spring conditions would reduce tree water status enough to alter their tissues' dielectric properties and thereby change the backscattering intensity or the polarization.

5. *Airborne Visible–Infrared Imaging Spectrometer (AVIRIS).*—AVIRIS is NASA's only instrument capable of producing high-spectral-resolution data. It generates images with 228 continuous spectral bands, each ≈10 nm bandwidth, covering the spectral range from 400 to 2400 nm. AVIRIS operates from NASA's ER-2 aircraft, producing images with a spatial resolution of ≈25 m. For OTTER, AVIRIS data were used to assess whether differences in biochemical composition between sites or over time could be estimated reliably, using mainly data from the shortwave infrared portion of the data. The relatively narrow bandwidths in the visible also give hope that variations in chlorophyll content or shifts in the red edge associated with chlorophyll could be measured (see Johnson et al. 1994, Matson et al. 1994 [this issue]).

6. *Advanced Solid-state Array Spectrometer (ASAS).*—This unique new instrument provides fairly high spectral-resolution data in the range from 400 to 900 nm and does so for seven different viewing angles. The sensor acquires images at 15° intervals relative to the aircraft's direction of flight starting at 45° forward viewing and going to 45° backward viewing. Thus, it produces at least one nadir viewing image corresponding to all of the other optical sensors. ASAS also operates from NASA's C-130 aircraft, producing images with a spatial resolution of ≈20 m. ASAS data are being studied using a geometric optics model to estimate standing biomass and hemispherical albedo (Abuelgasim and Strahler 1994). The data can also be used to estimate biophysical parameters such as LAI using the off-nadir view angles, which may reduce confounding effects due to open canopies and contrasting backgrounds. The hemispherical albedo calculations will be used to adjust estimates of IPAR and to adjust directional observations for bi-directional canopy reflectance variations.

7. *Compact Airborne Spectrographic Imager (CASI) and Fluorescence Line Imager (FLI).*—These two instruments were provided by Canadian investigators John Miller of York University (Toronto, Ontario, Canada) and his associates. These sensors produce the highest spectral resolution of any sensor used in OTTER, ≈2 nm throughout the visible to near infrared. They operate from various light aircraft and can produce images with spatial resolutions of ≈2 m. The high spectral and spatial resolutions could not be obtained simultaneously, so we chose to acquire the full spectral resolution data for a subsample of lines across the image, with one spectral channel devoted to full spatial resolution imaging. This spectral resolution resolves many fine spectral features due to atmospheric and biospheric phenomena that are not resolved on the other sensors. The data are being analyzed using models to extract chlorophyll, LAI, and tree density information (see Gong et al. 1992, Matson et al. 1994 [this issue], Spanner et al. 1994 [this issue]).

8. *Ultralight aircraft carrying a variety of instruments.*—This project is the first of NASA's to employ an ultralight aircraft as a sensor platform. The aircraft does not possess enough payload capacity to carry the heavy sensors described above, but was equipped with several pointing instruments, two spectroradiometers (the same as used on the ground), a stereo video camera for continuous imaging, and a thermal sensor. This unique platform offers many advantages for ecological studies due to its readiness, relatively inexpensive operation, reasonable stability, and slow speed—and the techniques developed by R. McCreight to optimize its use for sensing. Using on-board reference panels, the aircraft can cruise at various altitudes and thereby measure variations with altitude in the atmospheric optical properties. Being located on site, this aircraft was able to operate virtually anytime pending suitable weather conditions. The data collected from the ultralight aircraft are used to calculate NDVI and surface temperatures for the estimation of stomatal resistance, having corrected for atmospheric effects using the reference panel measurements during the flight. The data can also be used to cross-check other sensors.

Atmospheric corrections

Under all conditions the atmosphere scatters radiation and absorbs radiation, causing additive and transmissive effects on airborne sensor data. In OTTER we had sensors operating at many different altitudes (from 300 to 20 000 m) and throughout 2 yr and four seasons. In addition, forest fires in August added an extra atmospheric burden to the data. Over such large climatic extremes, even for "clear" days, these effects can sometimes dominate the sensor signals, particularly in the visible region. Clearly, they must be removed or minimized (see Spanner et al. 1994 [this issue]).

We used three methods to correct for these effects. First, during the overflights of the campaigns, and as near as possible to the actual time when the aircraft were above each site, two portable sunphotometers were moved across the transect to each site to make direct measurements of the spectral solar irradiance. The sunphotometer makes irradiance measurements in 10 narrow spectral bands in the visible and near infrared regions. These measurements are used with instrument calibrations to calculate aerosol optical depths. Using the model developed by Wrigley et al.

(1992), Rayleigh and aerosol scattering effects are used to correct the image data for atmospheric turbidity (see Johnson and Peterson 1991, Spanner et al. 1994 [this issue]). The second means of correcting for atmospheric optical contributions was with the reference panel measurements made on board the ultralight aircraft described above. By making observations at various altitudes and then regressing back to ground level, the ultralight data could be corrected for these effects. The third method employed the spectrally "flat" fields. Each field was carefully measured using field spectroradiometers and then sensor data over each field could be utilized to normalize for atmospheric variations.

Data Storage and Retrieval

Efforts in interdisciplinary science necessitate sharing of the large amounts of data generated among investigators—particularly with the use of remote sensing. Data base management has become an advanced technology that can minimize many of the difficulties associated with maintaining such complex data sets, with disseminating the data among collaborators, and with archiving and preservation of data for future use. Active research projects such as OTTER need an interactive data system. We accomplished this by coupling two existing data systems, one from NASA and one from Oregon State University, and expanding their services from archiving to include interactive roles such as rapid retrieval of data (Skiles and Angelici 1993).

NASA had established the Pilot Land Data System (PLDS) for managing NASA's remote-sensing data, for maintaining documentation about data files in the data bank, for providing a user interface to this documentation, and for the ordering of data sets. Prior to OTTER, PLDS had been mainly used for archival functions and had not been used to support an active science project. Active project support requires more interactive communication and customized extensions of services to accomplish data base tasks.

PLDS does not manage the kinds of ecological and meteorological data generated in OTTER. At Oregon State University the National Science Foundation, through its Long-Term Ecological Research (LTER) projects, is supporting the development of a more interactive data management system under the direction of S. Stafford of the Department of Forest Science with her associate, G. Spycher. This data base was used to store and provide access to most of the ecological and meteorological data sets. An electronic link between the LTER data system at Oregon State University and the PLDS node at Ames Research Center was established so that scientists could reach both of them through one interface, the PLDS one. Small data files were maintained on line for immediate access via communication networks, while the large digital image data sets had to be ordered and filled using other media.

During the final year of the project (1993), the carefully documented and validated data sets (a subset of the full data taken) have been mastered onto four CD-ROM disks. The disks include both the ecological and meteorological data as well as spectral image data sets. These disks will be the main medium for disseminating the OTTER data sets to a wide community.

Organization

The OTTER project was initiated at a NASA-sponsored workshop. A core of investigators with previous experience working in Oregon were present from NASA Ames Research Center, Oregon State University, the University of Montana, and the University of Maryland. We saw for the first time an opportunity to bring together many different and previously developed science techniques into a coordinated project. And we recognized a need to understand dynamic ecosystem processes that we could address with remote-sensing technology and computer modeling. Rather than continue to modify and perfect the modeling and remote sensing, we chose to conduct a test to see how well the existing models and algorithms could predict the processes they were designed to predict. A combined ground measurement, remote-sensing, and modeling proposal was generated to serve as the nucleus for attracting cooperating scientists. We knew from experience the need for ground validation and correlation data, and chose to install meteorological stations near each site for continuous monitoring of these data. Given the emphasis on the dynamical aspects of ecosystem function, we recognized the need for year-round coverage by aircraft and satellite sensing. The data base management activity was added to the core project as a prototype experiment in the ecological sciences to evaluate the needs of this community. In addition, a number of independently funded scientists and their instruments were attracted to the project on the basis of the value of collecting new or making unique analyses of shared data. These added investigations were complementary to the core efforts rather than redundant, and significantly expanded the scope of the effort. In addition, we succeeded in a proposal for special NASA designation as a Multi-sensor Aircraft Campaign (MAC) to secure better priorities in scheduling and access to these resources.

In any complex project such as OTTER, problems must be expected to arise that compromise some of the original objectives. We tried to minimize these through setting priorities, maintaining open and frank communication, through semi-annual team meetings, and through the use of electronic mail.

The close proximity of the study location, mid-state Oregon, to the NASA Ames Research Center (Moffett Field, California) was an advantage that is not always generally available. Ames is the home of NASA's main platform aircraft (ER-2, DC-8, and C-130). The coordinator for the MAC, M. Spanner, being at Ames helped significantly to explain the scientific reasons for our requirements to the aircraft program mission man-

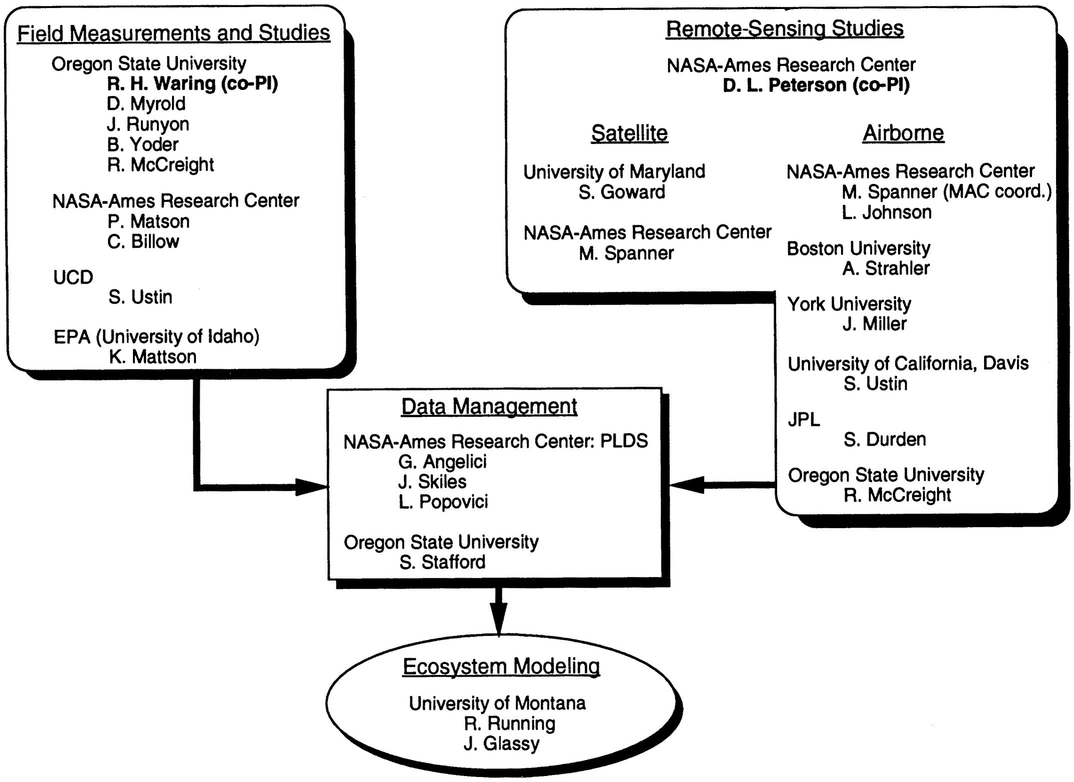

FIG. 2. Organizational structure and areas of responsibility for OTTER. PI = principal investigator; NASA = National Aeronautics and Space Administration; UCD = University of California at Davis; EPA = U.S. Environmental Protection Agency; JPL = Jet Propulsion Laboratory (Pasadena, California); PLDS = pilot land data system.

agers, to plan and then coordinate the often conflicting and compromising problems and operational issues during the campaigns, and to facilitate the delivery of the data acquired. For example, sensor malfunctions, poor weather conditions for clear sky viewing, absence of key ground and aircraft personnel, and so forth altered schedules. In addition, when an occasional flight opportunity was missed due to one or more of these problems, we were able to reschedule such flights for future and comparable time periods. In this way, we managed to acquire virtually all of the data we planned to acquire. Ultralight aircraft were unavailable early in the project, but became available during the first year. This aircraft provided important data in its own right as well as redundant or backup data to fill in important holes in data acquisition.

Fig. 2 provides a simplified diagram of the organizational structure and responsibilities in OTTER. The four main areas of responsibility were: (1) Ground measurements, (2) Remote-sensing measurements, (3) Ecosystem modeling, and (4) Data management. All decisions regarding ground-based measurements in Oregon were ultimately the responsibility of the coprincipal investigator, R. H. Waring and his colleague, D. Myrold. The other co-principal investigator, D. L. Peterson, coordinated all exchanges between NASA Centers and other groups interested in providing remote-sensing capabilities to the project. M. Spanner at Ames Research Center coordinated the operation of all aircraft involved in the project. S. W. Running and his colleagues at the University of Montana directed the ecosystem modeling effort and interacted with all members of the research team. G. L. Angelici of the Ames PLDS staff held responsibility for coordinating data management and for the links to the Oregon State University systems, while J. W. Skiles provided the day-to-day interactions and responses with all members of the science team. A number of the OTTER remote-sensing scientists brought a theoretical understanding to the project, led by S. Goward at the University of Maryland, L. Johnson of Ames, J. Miller of York University, and A. Strahler of Boston University. The inclusion of the ultralight aircraft was largely made possible by the efforts of R. McCreight. Many other investigators brought their own instruments and planes to participate in the OTTER project. With these contributions, the project gained nearly the full measure of remote-sensing capabilities that could be applied to terrestrial research at this time.

CONCLUSION

The OTTER project took advantage of three opportunities. The OTTER project was a natural next step and extension of previous research in Oregon and elsewhere. The earlier development of the general ecosystem model, FOREST-BGC, was an essential prerequisite for the project. The model included the key driving variables that we believed could be retrieved from remote-sensing data and would allow comparisons to be made across a wide range of coniferous ecosystems from different climate regimes and to be treated in various ways. Thus, the existence of and the need for validation of predictive ecosystem models for eventual extrapolation to larger geographic regions provided the first opportunity and motivated the project.

A second opportunity had to do with the history of research in Oregon. Much of the understanding of the effects of climate on physiological responses of the vegetation had been developed in the past in Oregon. And much of the destructive sampling needed to develop the allometric equations predicting forest structure from more easily measured properties were already available in Oregon for a wide variety of species, avoiding the necessity of doing such work beforehand. The LTER data system at Oregon State University maintained most of this past research in their data bases for ready access.

In addition to the earlier ecological research, a number of key remote-sensing studies had been conducted in Oregon using similar transects. Thus, a base of understanding and relationships had already been established on which to build the project and that would permit a realistic appraisal of expected results. This was part of NASA's decision to support OTTER and to designate the project as a Multi-sensor Aircraft Campaign (MAC). The completeness of the measurement strategy attracted other scientists, particularly some from the remote-sensing science community, a key factor in awarding MACs. This third opportunity, combined with the close geographic proximity of the transect to Ames' aircraft base, was critical for successfully conducting a project that demanded such a large commitment of aircraft time and duration.

Finally, we note that no attempt was made to achieve permanent growth in staff at any institution during the course of the project. OTTER is a good example of collaborative science by geographically separated parties. Clear and shared objectives, and clear policies for bringing in new participants to avoid duplication, to maintain intellectual propriety, and to assure cooperation were important to the project's success. A spirit of tolerance and cooperativeness characterized the project. No single institution has or probably will have all of the scientific expertise required for such research efforts, so an open and shared leadership style is necessary to encourage participation by other groups. In addition to the roles of the university participants, scientists from three other NASA Centers (Jet Propulsion Laboratory, Goddard Space Flight Center, and Marshall Space Flight Center) joined OTTER. And staff from the U.S. Environmental Protection Agency and the USDA Forest Science Laboratory in Oregon also were active in the project. Perhaps the temporary confederation model used by the OTTER project offers a flexible alternative to assembling a large temporary staff for a single project or for assigning resident staff to critical tasks that they have not previously mastered. While this puts a heavier burden on communication, it improves interaction among scientists and allows for building good team strength and cooperation.

The articles published in this special feature are among the first reports of the OTTER project. Another set appears in *Remote Sensing of Environment* **47**(2) along with papers from a separate NASA-sponsored MAC called the Forest Ecosystem Dynamics Project. We also anticipate many other single papers in the near future, particularly those dealing with the nutrient-cycling aspects of OTTER. We hope that these and other studies merging the talents of ecologists with those of the remote-sensing community will prepare the way for a better understanding of how the biosphere operates at regional and global scales.

Acknowledgments

While this and other papers in this issue give credit to many of the principal participants in the OTTER project, a host of other people made significant contributions to the project. This list is long indeed and should include the efforts of many people making field measurements in support of specific research tasks, the efforts of the NASA Aircraft Program and other aircraft personnel who assured that the data missions were a success, and the personnel who assured that the data were managed with certainty. Helpful comments were received on the earlier drafts of this manuscript by Tony Janetos, Beverly Law, Rich McCreight, Barbara Yoder, John Runyon, and Jeanne Panek. This work was supported by NASA grants NAGW-1717 to Oregon State University and many related grants to other participants.

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